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14. ABSTRACT

Laser-powered lightcraft systems that deliver microsatellites to low earth orbit have been studied for the Air Force Research Laboratory. One result of this Study has been discovery of the significant influence of laser wavelength on the power lost during laser beam propagation through Earth's atmosphere and in space. Here, energy and power losses in the laser beam are extremely sensitive to wavelength for earth-to-orbit missions. And this significantly affects the amount of mass that can be placed into orbit for a given maximum amount of radiated power from a ground-based laser.

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Study to Determine the Effectiveness and Cost of A Laser-Powered "Lightcraft" Vehicle System —Results to Guide Future Developments

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Abstract. Laser-powered lightcraft systems that deliver microsatellites to low earth orbit have been studied for the Air Force Research Laboratory. One result of this Study has been discovery of the significant influence of laser wavelength on the power lost during laser beam propagation through Earth's atmosphere and in space. Here, energy and power losses in the laser beam are extremely sensitive to wavelength for earth-to-orbit missions. And this significantly affects the amount of mass that can be placed into orbit for a given maximum amount of radiated power from a ground-based laser.

INTRODUCTION

This paper summarizes certain aspects of a Study that examined the effectiveness and cost of a "lightcraft" vehicle powered by a high-energy laser beam. The Study, performed for the Air Force Research Laboratory (AFRL), built on the extensive lightcraft laser propulsion technology already developed by theoretical and experimental work by the AFRL and others. The major study objective was to identify those areas where lightcraft and laser research should be amplified or redirected. The work associated with this Study was performed primarily by: Flight Unlimited (FU), McKinney Associates (MKA), and Defense Strategies & Systems Inc. (DSAS). The Study was accomplished under the direction of Dr. Franklin Mead and with the assistance of Dr. William Larson. The Study was performed during the period between 12 October 2000 and 30 June 2003. As indicated by the flow diagram, shown in Figure 1, the Study identified and developed a cost model for a laser-powered lightcraft space transportation system by a multi-disciplinary optimization approach.

The multi-disciplinary optimization approach endeavored to maximize payload mass delivered to orbit by: optimal management of the laser energy propagated to the lightcraft by the laser beam; and by optimal utilization of the propagated laser energy by lightcraft laser propulsion. This, as shown in Figure 1, required continual iterations within: a System Definition block of activity managed by FU; a Trajectory Optimization block of activity, using the "Optimal Trajectory Integration System" (OTIS), managed by MKA; and a Life-Cycle Costing block of activity by both FU and MKA. Costing activity also utilized lightcraft and laser cost data obtained from the AFRL.

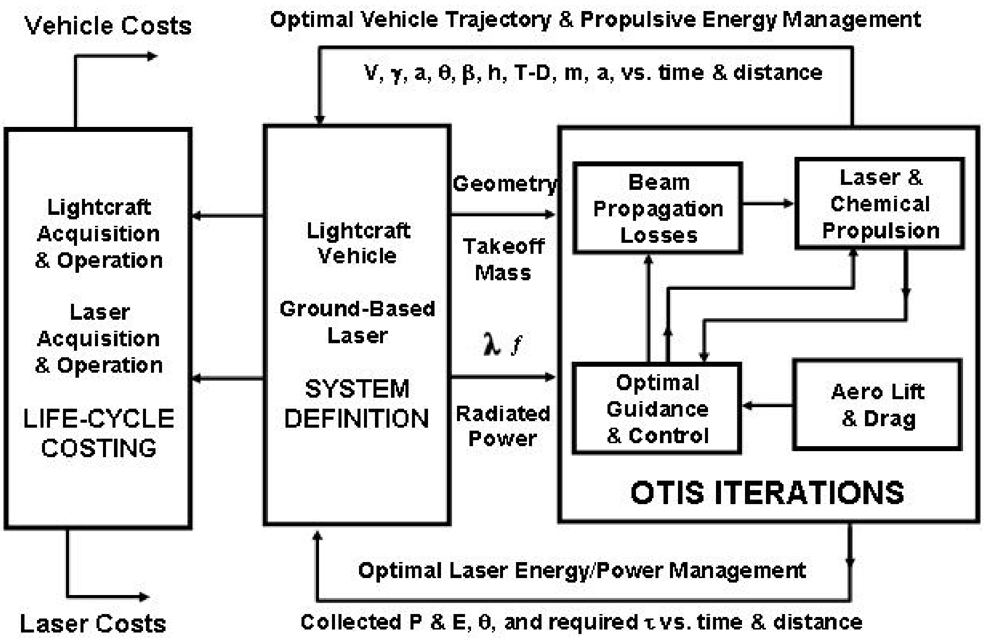

Figure 1. Study Flow.

LIGHTCRAFT MISSION AND VEHICLE DEFINITION

Mission analysis performed during the Study revealed numerous Air Force missions that could benefit from laser propulsion. However, superiority of laser propulsion over chemical rocket propulsion was deemed to be best for earth-to-orbit transportation missions, entailing rapid deployment of many small light-weight satellites around the Earth. Although different lightcraft geometries and masses were considered, the general lightcraft concept used in the mission and subsequent work was similar to that of the numerous Air Force Lightcraft, that have been success-fully tested with the PLVTS pulsed carbon dioxide laser at the White Sands Missile Range in the United States [1].

As shown in Figure 2, the lightcraft vehicle concept consists of: (1) a conically shaped "forebody" for lift and aerodynamic compression of ingested airflow (prior to its detonation by laser heating during atmospheric flight); (2) an annular "cowl" or "shroud" structure—within which air detonation or propellant ablation (by intense laser heating) occurs; and, (3) a parabola-shaped "afterbody" whose mirrored surface focuses beamed laser energy into regions of sufficient smallness within the cowl for intense air or propellant heating to occur. The vehicle is powered by laser airbreathing propulsion (by detonation of air) until hypersonic speed within the sensible atmosphere is reached; and then the vehicle is powered by laser rocket propulsion (by heating of propellant) during flight above the sensible atmosphere and in space, until the needed velocity for orbital flight is reached.

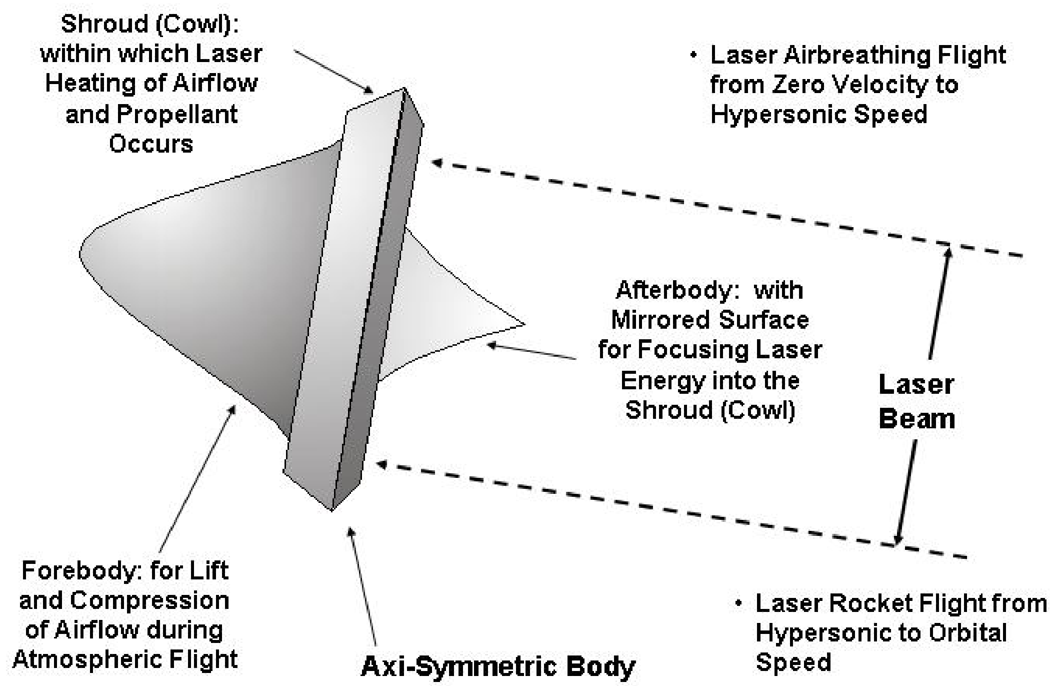

Figure 2. Lightcraft Vehicle Concept.

PROPAGATION LOSSES WITHIN LASER BEAMS

An important Study finding was the significant influence of the ground-based laser wavelength on lightcraft performance. Figure 3 illustrates the adverse beam propagation geometry associated with Earth-to-orbit laser propulsion by ground-based lasers (GBL). It is seen that beam propagation distances through Earth's atmosphere are short during initial flight phases, when the path length traveled by laser energy to the lightcraft is least. But during latter flight phases (when the vehicle itself is above the sensible atmosphere) the beam propagation path within the atmosphere is much longer, and power losses due to atmospheric attenuation become ever greater with increasing range. And since power losses due to laser beam-spreading, even in vacuum, also increase with increasing distance from the laser, power losses are greatest at the end of laser propulsion (e.g., when vehicle distance from the laser is longest).

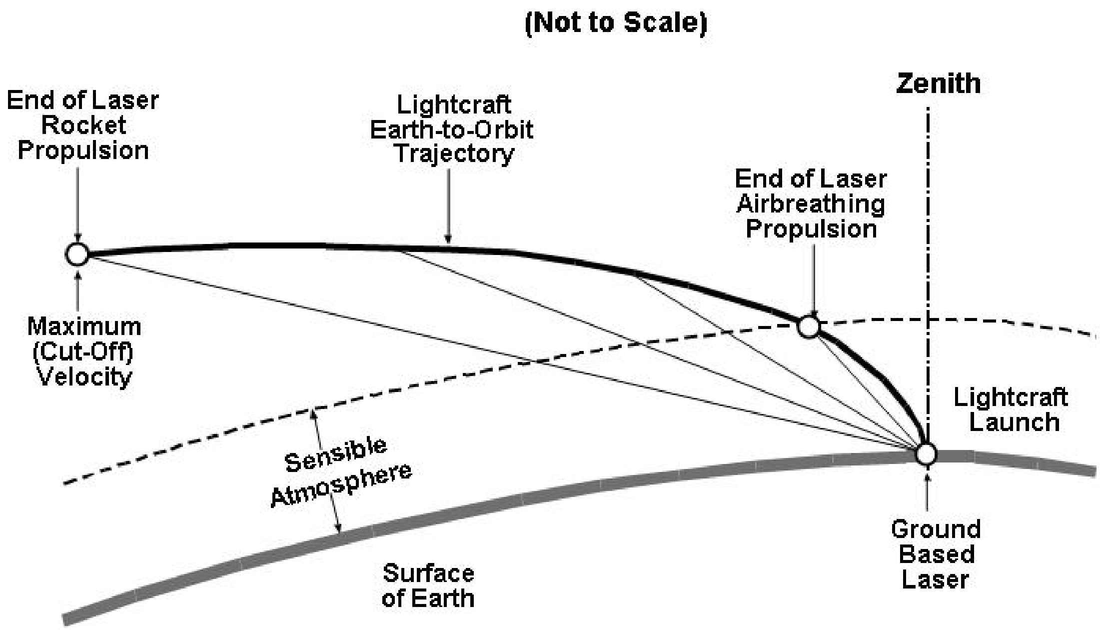

Figure 3. Lightcraft Earth-to-Orbit Trajectory.

The major contributors to energy loss within laser beams are: (1) “diffraction” caused by the beam-spreading associated with the laser aperture diameter and the wavelength of the pulsed laser radiation; (2) “thermal blooming” associated with air heating by the laser beam; (3) “turbulence” within the continual movements of various currents of air; (4) “scattering” by photon reflection off the molecular structure of air particles; and, (5) “extinction” from total photon energy absorption within regions of fog or air. Figure 4 by DSAS illustrates the optimization problem associated with balancing the various loss mechanisms occurring within propagating laser beams. It is seen that laser wavelength choice influences the losses due to turbulence, scattering, and diffraction; and that significant thermal blooming and extinction occur within discrete regions of the possible laser wavelength spectrum. Thus, since each loss mechanism was a function of wavelength, DSAS considered each in its estimation of lost power for the 6 different laser wavelengths of the 6 different GBL candidates that were evaluated in the Study.

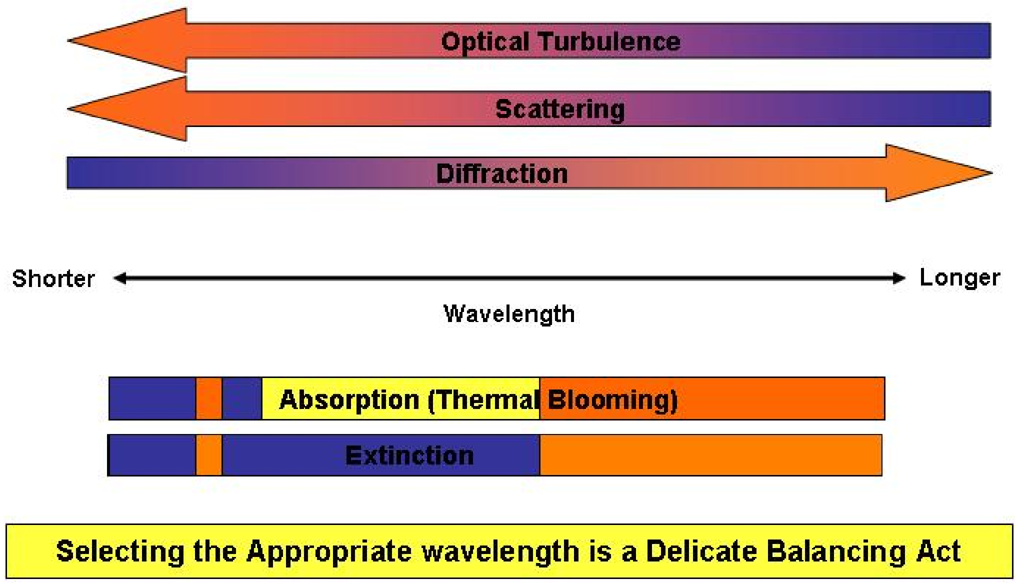

Figure 4. Balancing Loss Mechanisms**.**

For a given GBL: aperture diameter, adaptive optics, and atmospheric conditions, Figure 5 shows the influence of lightcraft range and laser-pointing angle on laser power captured by the lightcraft. Figure 5 illustrates the decrease in laser power collected by the lightcraft with increasing range, for an initial vertical laser pointing-angle and for a final laser-pointing angle that occurs at maximum laser propulsion range and maximum lightcraft speed. Also shown for the final laser pointing-angle, is the significant decrease in collected power if adaptive optics are not used.

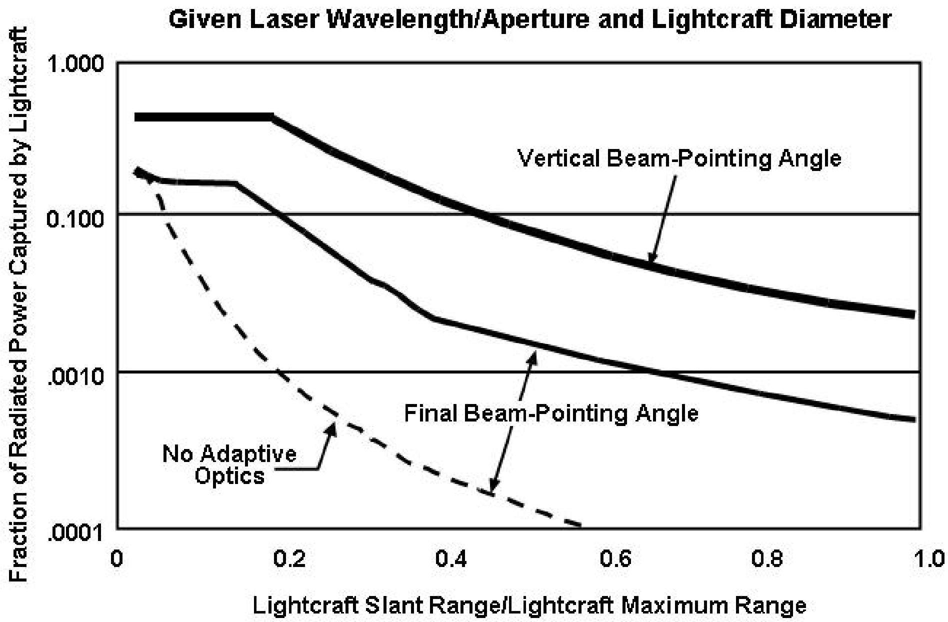

Figure 5. Influence of Lightcraft Range and Laser Pointing.

INFLUENCE OF WAVELENGTH ON COLLECTED LASER POWER

Figure 6 shows that there is a significant difference in the laser power collected by the lightcraft during its laser propulsion phase of flight for the best and worst laser wavelength investigated. This comparison is for the beam angles and ranges associated with a lightcraft trajectory determined from optimization work during the middle of the Study, and for the highest radiated power and the largest aperture deemed practical for Air Force operations and systems.

Six laser wavelengths were investigated to determine their propagation characteristics through the atmosphere and diffraction properties. There was an optimum wavelength which propagated best through the atmosphere. Figure 7 shows that significantly more power would be available for the six different investigated laser wavelengths at the end of laser airbreathing propulsion (where the laser beam propagation distance is relatively short) than would be available at the end of laser rocket propulsion flight. This, therefore, might benefit surface-to-air lightcraft missions that would entail airbreathing flight to slower-than-orbital speeds. Shown in Figure 8, is the fraction of radiated laser power collected by the lightcraft at maximum laser propulsion range (when necessary "cut-off" velocity for orbital flight is achieved) for the six wavelengths that were associated with the six GBL candidates that were investigated during the Study. It is seen that a significant fraction of laser-radiated power is lost, even if there were no atmospheric propagation losses at all. And additional losses associated with beam propagation through the atmosphere are seen to result in power losses of the order of 75% to 99%.

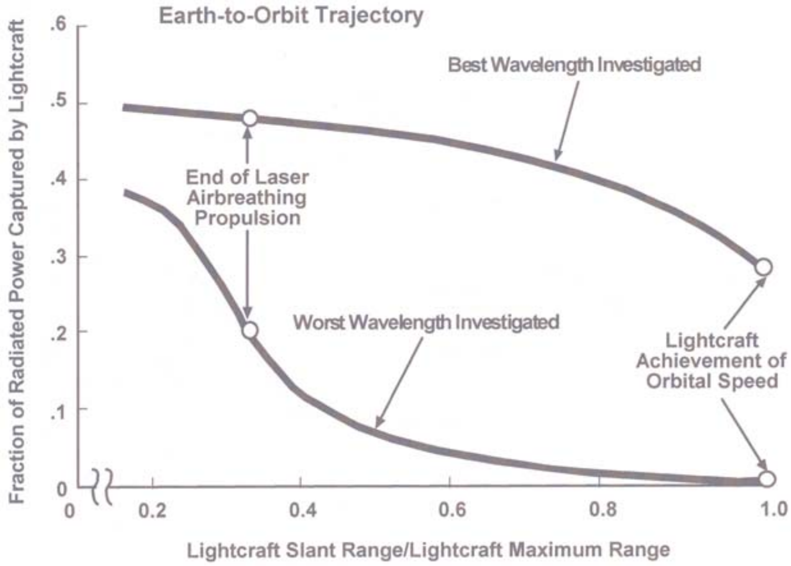

Figure 6. Influence of Wavelength on Laser Power Captured.

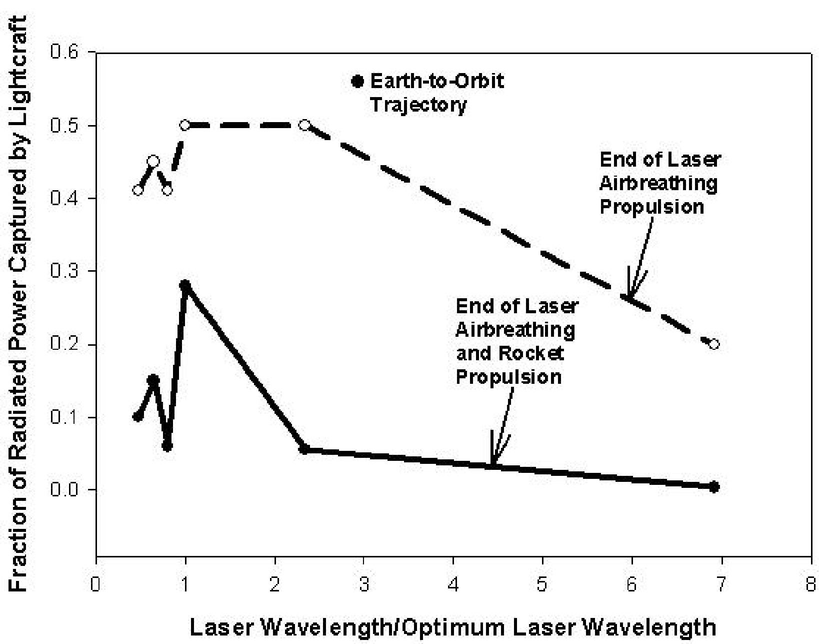

Figure 7. Influence of Wavelength on Laser Power Captured.

INFLUENCE OF LASER WAVELENGTH ON ORBITED MASS

Pioneering investigators, such as Kantrowitz [2], estimate that the mass that can be orbited by GBL's would be proportional to the power collectable from such lasers for propulsion. If this is true, masses that can be orbited by lightcraft are roughly proportional to the power collectable by them at the end of their laser propulsion phase of flight. Figure 9 uses this assumption to compare masses orbited by the 6 different lasers (with their 6 different wavelengths) for a given maximum value of radiated power from a ground-based laser. Figure 9, therefore, shows that orbited mass for a given level of laser-radiated power is extremely sensitive to laser wavelength. Thus, wavelength—together with other laser technical, operational, and cost issues—is an important consideration in ground-based laser selection for earth-to-orbit lightcraft.

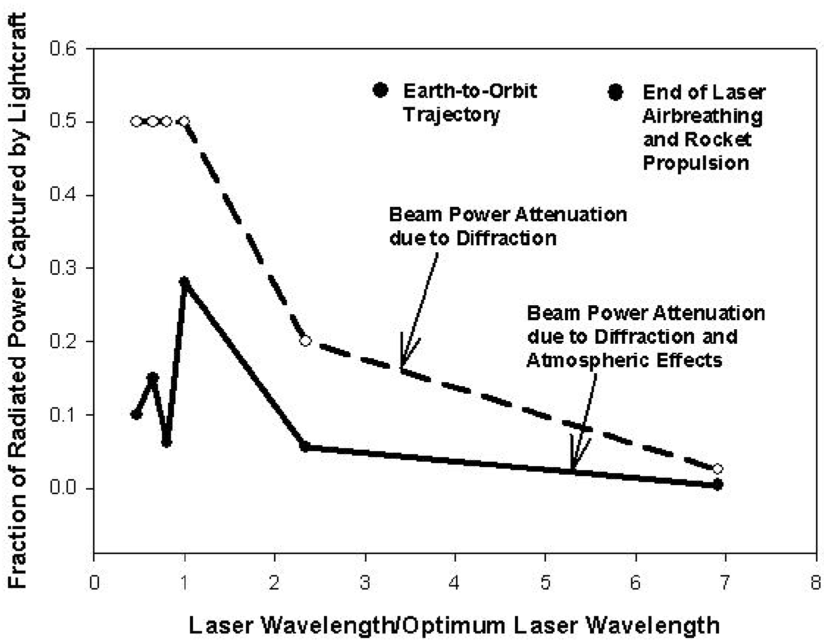

Figure 8. Influence of Wavelength on Laser Power Captured

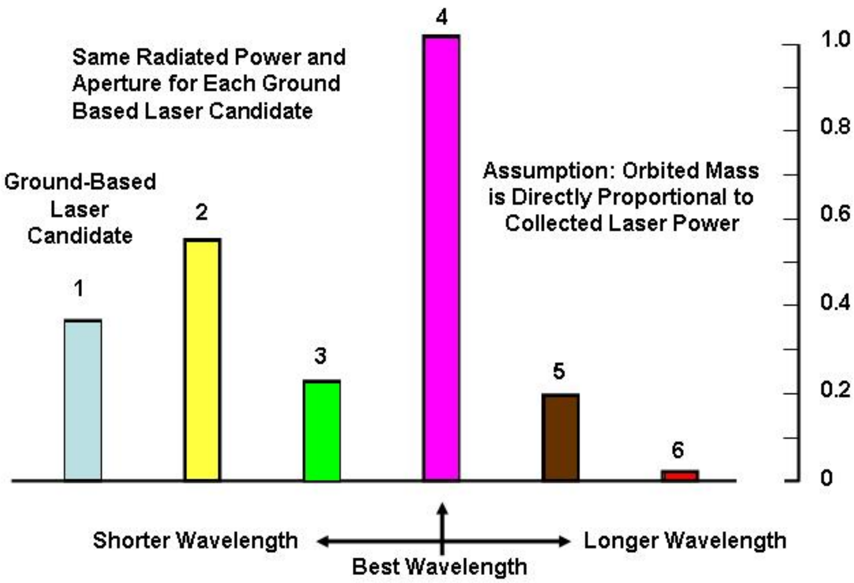

Figure 9. Influence of Laser Wavelength on Orbited Mass.

CONCLUSION

Energy and power lost during laser beam propagation through Earth's atmosphere and space is significantly influenced by the laser's wavelength. These losses are very significant for Earth-to-orbit missions involving laser propulsion, and they strongly influence the microsatellite mass that can be delivered to low-Earth-orbit for a given amount of maximum radiated power from GBL's. Thus, laser wavelength, together with other laser technical, operational, and cost issues, is an important consideration for Earth-to-orbit lightcraft.

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2. . Kantrowitz, A., "Propulsion to Orbit by Ground-Based Lasers," Astronautics & Aeronautics, Vol. 10, No. 5, May 1972, pp. 74-76.